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FRACTURE TOUGHNESS MEASUREMENTS OF THREE TITANIUM ALLOY EXTRUSIONS

ARMY MATERIALS AND MECHANICS RESEARCH CENTER

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THOMAS S. DeSISTO
METALS RESEARCH DIVISION

July 1973

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Watertown, Massachusetts 02172

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Technical Report by
THOMAS S. DeSISTO

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13. ABSTRACT

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Plane strain static K_{Ic} and dynamic, K_{Id} measurements were obtained on three-inch-diameter titanium alloy extrusions which received a 5.9:1 reduction followed by air cooling. The alloys investigated were Ti-6Al-6V-2Sn, Ti-8Mo-8V-2Fe-3Al, and Ti-11.5Mo-6Zr-4.5Sn (Beta III). Compact tension specimens were used to obtain K_{Ic} measurements and precracked standard Charpy V-notched specimens were used to obtain K_{Id} measurements. The highest K_{Ic} and K_{Id} values were obtained from the Beta III extrusion while the lowest K_{Ic} and K_{Id} values were obtained for the Ti-8Mo-8V-2Fe-3Al extrusion. Good agreement was found to exist between K_{Ic} values obtained from precracked Charpy V-notch specimens and compact tension specimens.

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INTRODUCTION

Titanium alloys offer a considerable strength/weight and corrosion resistance advantage over many engineering materials. Most mechanical properties are well documented and accepted. However, very little is known about the effects of heat treatment, process variables, and the resultant microstructures on the static fracture toughness properties K_{Ic} and the dynamic fracture toughness properties K_{Id} of titanium alloys in heavy section form such as in the Heavy Lift Helicopter main rotor drive shaft.

Chait and DeSisto,[1] in a study of the influence of microstructural variables on the fracture toughness of three heavy section titanium alloy extrusions, showed that K_{Ic} values of Ti-6Al-4V are highly dependent on primary alpha morphology. They also showed that an equiaxed microstructure results in higher K_{Ic} values than a plate-like microstructure. Adair and Roberson,[2] in a study on small section extrusions of Beta III, found that K_{Ic} values for water-quenched extrusions were slightly lower than air-cooled extrusions at the same yield strength level.

This study deals with the static and dynamic plane strain fracture toughness properties of three 3-inch-diameter titanium alloy extrusions which received an 83% reduction. The alloys studied were Ti-6Al-6V-2Sn, Ti-8Mo-8V-2Fe-3Al, and Ti-11.5Mo-6Zr-4.5Sn (Beta III). Compact tension specimens were utilized for the static K_{Ic} measurements and precracked Charpy V-notch specimens were utilized for the K_{Id} measurements.

MATERIALS

The materials used in this testing program were an alpha + beta alloy Ti-6Al-6V-2Sn and two metastable deep-hardenable beta alloys, Ti-8Mo-8V-2Fe-3Al and Ti-11.5Mo-6Zr-4.5Sn, which is referred to as Beta III. The chemistries of the three alloys are shown in Table I. The material was procured as 8-inch-diameter forged stock. Since the forging manufacturers did not have the tooling required to extrude an 8-inch-diameter bar, the bars were machined to 7-5/16-inch diameter. The 20-inch-long by 7-5/16-inch-diameter bars were prepared for extrusion by machining a 1/2-inch radius on the leading edge. The bars received an 83% reduction to 3-inch diameter. As water quenching facilities were not available, the bars were air cooled after extrusion. The extrusion histories are shown in Table II.

The extruded bars were heat treated as shown in Table III. The microstructures obtained after solution treating and aging are shown in Figure I. The microstructure of the Ti-6Al-6V-2Sn is elongated primary alpha in a transformed

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[1]CHAIT, R., and DeSISTO, T. S. *The Fracture Toughness of Three Heavy Section Titanium Alloys.* Army Materials and Mechanics Research Center, AMMRC PTR 72-5, October 1972.

[2]ADAIR, A. M., and ROBERSON, J. A. *The Influence of Thermomechanical Processing on the Structure and Properties of Extruded Beta III Titanium.* Proceedings of the Second International Conference on the Strength of Metals and Alloys, American Society for Metals, Metals Park, Ohio, 1970, p. 932-936.

beta matrix. The microstructures of both beta alloys consists of a fine alpha precipitate in a beta matrix. The ASTM grain sizes for the Ti-8Mo-8V-2Fe-3Al and the Beta III are 2-4 and 4-5, respectively.

TEST PROCEDURE

Threaded 0.252-inch-diameter tension specimens were used to obtain tension data. Three tension specimens were machined from both the longitudinal and transverse orientations. The test specimen layout is shown in Figure 2. Longitudinal tension specimens were prefixed by A and transverse tension specimens are prefixed by K. Longitudinal and transverse Charpy specimens are identified by L and P. The tension specimens were tested in a 120,000-pound hydraulic tension machine at

Table 1. CHEMISTRY

Ti Alloy	Element (Weight Percent)										
	Al	V	Mo	Fe	Sn	Cu	Zr	C	O	H	N
6Al-6V-2Sn	5.57	5.25	-	0.78	2.45	0.72	-	0.022	0.13	0.0104	0.017
8Mo-8V-2Fe-3Al	2.26	7.99	8.17	1.77	-	.006	-	.022	.16	.0070	.018
11.5Mo-6Zr-4.5Sn	-	-	11.2	0.05	4.70	-	5.70	.020	.13	.0009	.010

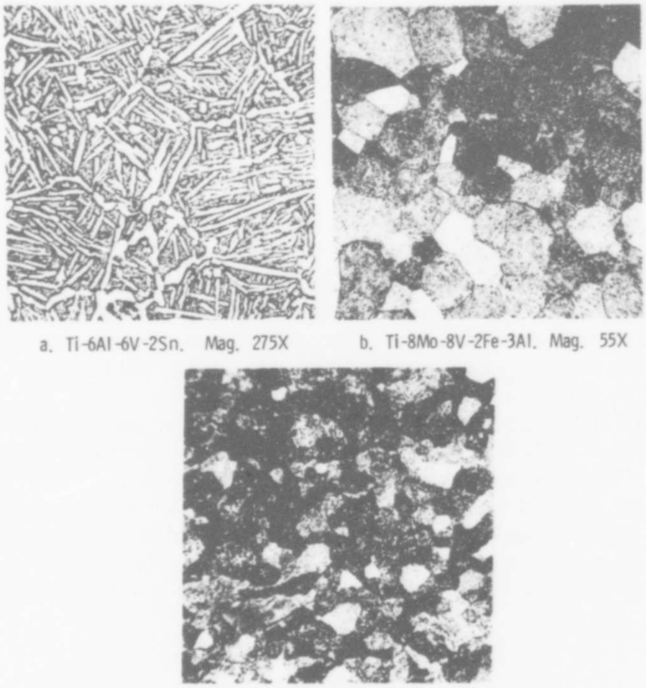
Table II. EXTRUSION HISTORY

Alloy	Ti-6Al-6V-2Sn	Ti-8Mo-8V-2Fe-3Al	Ti-11.5Mo-6Zr-4.5Sn
Extrusion Temp (deg F)	1735	1650	1500
Heating Time (min)	40	40	150
Heating Medium	$BaCl_2$	$BaCl_2$	Gas
Extrusion Pressure (T/in.^{2})	30.9 to 35.0	30.9 to 32.5	45.6 to 52.8
Lubrication*	#514	#514	#514
Die Design (included angle)	90°	90°	90°
K-Factor (×1000)	38.4	35.8	58

*Fiske Bros. #514 lubricant.

Table III. HEAT TREATMENT

Ti Alloy	Solution Treatment	Aging Treatment
6Al-6V-2Sn	1600 F - 1-1/2 hr - WQ	1250 F - 6 hr - AC
8Mo-8V-2Fe-3Al	1475 F - 1-1/2 hr - WQ	1000 F - 8 hr - AC
11.5Mo-6Zr-4.5Sn	1350 F - 1/2 hr - WQ	950 F - 8 hr - AC



a. Ti-6Al-6V-2Sn. Mag. 275X

b. Ti-8Mo-8V-2Fe-3Al. Mag. 55X

c. Ti-11.5Mo-6Zr-4.5Sn. Mag. 55X

Figure 1. Microstructure of Ti Alloys
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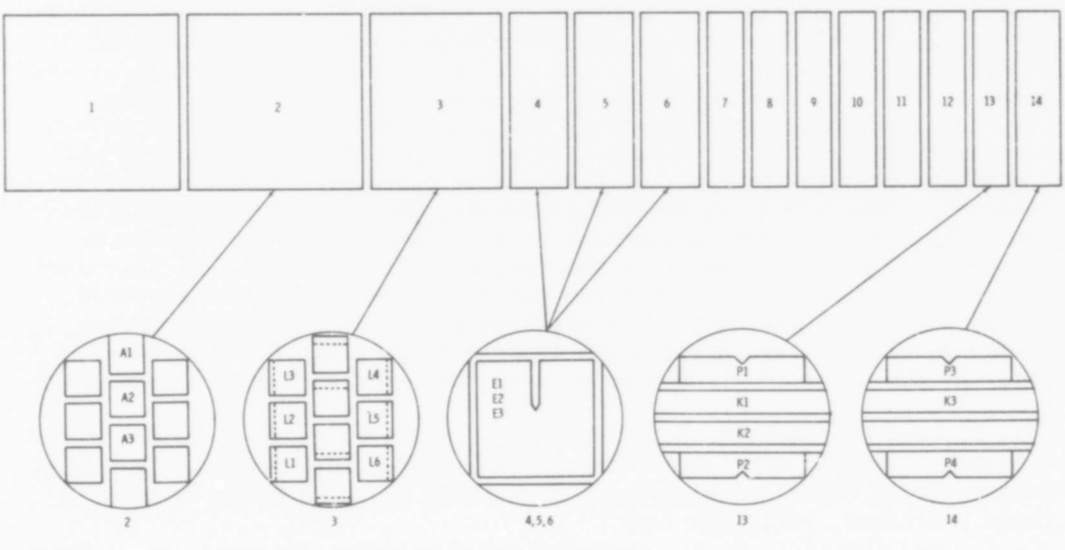


Figure 2. Test Specimen Layout

a platen speed of 0.005 inch/minute to fracture. An extensometer, which was used to obtain yield strength data, was removed after an offset of 0.2 percent was reached. After the extensometer was removed a device[3] positioned on the upper shoulder of the tension specimen was used to obtain diameter measurements for true stress-strain calculations. True stress at maximum load and fracture and the strain hardening exponent n were obtained from logarithmic plots of true stress and true strain.

Plane strain fracture toughness data K_{Ic} were obtained from 3/4-inch-thick compact tension specimens which were machined in the transverse orientation. This designation and the test procedure conformed to that specified in ASTM E399-72. Typical crack fronts, which are thumbnail in appearance, are shown in Figure 3. Because it is almost impossible to obtain straight crack fronts in solution-treated-and-aged titanium alloys, the data are considered valid.

Plane strain dynamic fracture toughness data K_{Id} were obtained by testing precracked standard 0.394 × 0.394-inch Charpy V-notched specimens in a computerized impact testing system.[4] Data were obtained at a hammer velocity of 17 feet per second. Charpy specimens, which were machined in both the longitudinal (L-R) and transverse (C-R) orientations, were precracked in a ManLabs Charpy fatigue pre-cracking machine. In addition, a ManLabs slow bend tester was used to obtain slow bend data from precracked Charpy specimens. The specimens were tested at a head speed of 0.025 inch per minute.

RESULTS AND DISCUSSION

Tensile Properties

The tensile properties obtained are shown in Table IV. It is noted that the longitudinal properties of the Ti-6Al-6V-2Sn and Beta III alloys are higher at the outer wall location than the core location. The higher tensile properties of Ti-6Al-6V-2Sn material at the outer wall location is characteristic of the alloy and is attributed to its poor hardenability in large section sizes. This trend, however, was not expected for the deep-hardenable Beta III alloy. A high degree of tensile anisotropy existed in the Beta III extrusion. The transverse midwall yield and ultimate tensile strengths were 21 and 17 ksi higher than the longitudinal properties. True stress at fracture, however, was not affected by specimen orientation. The strain hardening exponent n of the transverse core specimens was approximately 50 percent lower than the longitudinal specimens. An anomalous behavior in tensile properties was observed for the Ti-8Mo-8V-2Fe-3Al material. The tensile properties at the outer wall location are lower than at the core location. The abnormally low longitudinal tensile properties of the Ti-8Mo-8V-2Fe-3Al alloy at the outer location also occurred on 3-inch-diameter bars of the

[3]DeSISTO, T. S., and DRISCOLL, D. E. *Effect of Strain Rate and Temperature on the True Stress - True Strain Properties of Commercially Pure Titanium* in High Speed Testing, v. 1, First Annual Symposium, Boston, Mass., 8 December 1958, Interscience Publisher, Inc., New York.
[4]CARTER, C. J., and CELLITTI, R. A. *Computerized System for Improved Impact Test Material Evaluation.* International Harvester, Contract DAAG-46-69-C-0005, Final Report, AMMRC CR 71-16, September 1971.

same heat which were extruded at temperatures of 1850 F and 2000 F. The differences in strength level are assumed to be caused by either time at solution temperature and/or cooling rate.

The orientation of the compact tension specimen is such that the fatigue precrack terminates at the center of the 3-inch bar. Therefore, only transverse tensile core properties are of importance in the fracture toughness evaluation. Detailed comparison of tensile properties is part of another study and will be reported in a future publication.

Table IV. TENSILE PROPERTIES

Ti Alloy	Spec. Ident.	Orien-* tation* & Loca- tion	0.2% YS (ksi)	TS (ksi)	True Stress at Max Load (ksi)	True Stress at Fracture (ksi)	n Strain Hardening Exponent	Elon. (%)	R.A. (%)
6Al-6V-2Sn	6A1	L, O	152.1	165.9	190.8	250.2	0.14	26.0	45.2
	6A2	L, M	141.7	159.9	181.0	226.2	.12	20.0	39.2
	6A3	L, M	142.3	159.5	182.2	227.5	.13	20.0	39.2
	Avg.		145.4	161.8	184.7	234.6	.13	22.0	41.2
6Al-6V-2Sn	6K1	T, M	140.7	156.7	180.2	226.2	.14	20.0	39.2
	6K2	T, M	141.1	157.5	175.1	220.6	.11	19.0	37.8
	6K3	T, M	146.5	161.1	182.3	222.1	.12	19.0	36.6
	Avg.		142.8	158.1	179.2	223.0	.12	19.0	37.9
8Mo-8V-2Fe-3Al	8AA1	L, O	145.9	162.7	182.5	182.5	.12	10.0	11.0
	8AA2	L, M	153.3	164.3	172.6	172.6	.05	5.0	5.7
	8AA3	L, M	154.8	165.8	176.9	176.9	.06	5.0	5.3
	Avg.		151.3	164.3	177.3	177.3	.08	6.7	7.3
8Mo-8V-2Fe-3Al	8AK1	T, M	156.3	167.1	174.1	174.1	.04	3.0	4.2
	8AK2	T, M	155.1	168.3	176.0	176.0	.05	4.5	5.0
	8AK3	T, M	154.3	169.8	182.7	182.7	.07	5.0	5.3
	Avg.		155.2	168.4	177.6	177.6	.05	4.2	4.8
11.5Mo-6Zr-4.5Sn	7A1	L, O	167.1	181.2	198.2	221.2	.09	10.0	24.7
	7A2	L, M	156.1	174.7	189.6	210.9	.08	10.0	23.4
	7A3	L, M	156.3	173.5	191.6	208.3	.10	12.0	22.6
	Avg.		159.8	176.5	193.1	213.5	.09	10.7	23.6
11.5Mo-6Zr-4.5Sn	7K1	T, M	176.4	190.4	195.1	217.2	.03	7.0	16.2
	7K2	T, M	177.0	190.8	203.4	219.3	.06	9.0	17.0
	7K3	T, M	177.4	191.6	201.3	201.3	.05	6.0	-
	Avg.		176.9	190.9	199.9	212.6	.05	7.3	16.6

*L = Longitudinal
T = Transverse
O = Outer Wall
M = Midwall

Fracture Toughness Properties

Ti-6Al-6V-2Sn

The alpha + beta alloy Ti-6Al-6V-2Sn was overaged at 1250 F (STOA condition). Transverse yield strength at the core of the extruded section was the same as that previously obtained in tests of a cylindrical 8-3/4-inch O.D. × 2-3/4-inch I.D. extrusion aged at 1300 F.[1] The low yield strength of the 3-inch extrusion at the 1250 F aging temperature was due to the difference in oxygen content, 0.13 percent for the 3-inch extrusion and 0.16 percent for the cylindrical hollow extrusion.

The K_{Ic} values obtained for the STOA condition showed very little variation, 52 to 54.5 ksi$\sqrt{\text{in.}}$, Table V. These values, while high, were considerably lower than the 64 to 73.5 ksi$\sqrt{\text{in.}}$ values reported for 8-3/4-inch O.D. cylindrical hollow extrusions with a 3-inch wall thickness.[1] The increased toughness of the cylindrical extrusion is attributed to the equiaxed primary alpha microstructure which has been shown to enhance fracture toughness.[1] The rather large shear lips evident on the fractured surface shown in Figure 3 is further evidence of the high toughness of the alloy.

Dynamic fracture toughness values K_{Id} obtained from precracked Charpy V-notch specimens are shown in Table VI. Maximum load obtained from the load-time trace was used in the ASTM E399-72 three-point bend equation to calculate K_{Id}. The maximum load, however, was not corrected for inertial effects. K_{Id} values of 44.4 and 45.5 ksi$\sqrt{\text{in.}}$ obtained on transverse specimens were considerably lower than the 52 to 54.5 ksi$\sqrt{\text{in.}}$ obtained on compact tension specimens. The low K_{Id}/K_{Ic} ratio of 0.84 is an indication of the moderately high strain rate sensitivity of the Ti-6Al-6V-2Sn alloy.

Table V. K_{Ic} MEASUREMENTS OF TITANIUM ALLOY EXTRUSIONS

Material	a in.	W in.	B in.	P_Q lb	a/W	K_{Ic} ksi$\sqrt{\text{in.}}$	$\frac{P\ Max.}{P_5}$	$2.5\left(\frac{K_{Ic}}{\sigma y}\right)^2$
Ti-6Al-6V-2Sn	0.783	1.499	0.749	4860	0.522	54.5	1.00	0.365
	.808	1.488	.750	4325	.543	52.0	1.02	.332
	.779	1.496	.750	4850	.521	54.2	1.00	.361
	Avg.					53.6		
Ti-11.5Mo-6Zr-4.5Sn	.773	1.499	.750	5030	.516	55.2	1.02	.243
	.790	1.499	.751	4680	.527	53.2	1.02	.226
	.789	1.499	.750	5010	.526	56.8	1.00	.258
	Avg.					55.1		
Ti-8Mo-8V-2Fe-3Al	.747	1.498	.750	3290	.498	34.1	1.04	.121
	.7755	1.4995	.750	3300	.517	36.3	1.01	.137
	.766	1.498	.750	3180	.511	34.3	1.01	.122
	Avg.					34.9		

Because of the low 2.5 $(K_{Ic}/\sigma_y)^2$ size requirement, 0.332 to 0.365 inch (Table V), K_{Ic} measurements were obtained from precracked Charpy V-notched specimens tested in three-point bending. The value of 47.0 ksi$\sqrt{\text{in.}}$ shown in Table VII is reasonably close to the static K_{Ic} value and indicates that slow bend testing can be used for screening purposes.

Ti-8Mo-8V-2Fe-3Al

A previous study[1] on the same heat of Ti-8Mo-8V-2Fe-3Al showed that for like heat treatment conditions, a wide range of toughness values and tensile ductility properties were obtained on a 3-inch-diameter press forging and an 8-3/4-inch O.D. cylindrical hollow extrusion with a 3-inch wall thickness. The 3-inch-diameter press forging received a 78 percent reduction at 1900 F while the cylindrical hollow extrusion received a 30 percent reduction at 1700 F. K_{Ic} values of 34.8 to 36.0 ksi$\sqrt{\text{in.}}$ were obtained from the 3-inch-diameter press forging at a yield strength of 181 ksi. Reduction of area values were 10 percent while the ASTM grain size was 3 to 5. K_{Ic} values of 51.5 to 52.1 ksi$\sqrt{\text{in.}}$ were obtained from the cylindrical hollow extrusion at a yield strength level of 177.7 ksi. Reduction of area values were extremely low, 3.3 percent, and the ASTM grain size of 0 was extremely large.

Table VI. K_{Id} MEASUREMENTS OF TITANIUM ALLOY EXTRUSIONS

Ti Alloy	Orientation	K_{Id} ksi$\sqrt{\text{in.}}$	K_{Ic} ksi$\sqrt{\text{in.}}$	$\frac{K_{Id}}{K_{Ic}}$
6Al-6V-2Sn	L	48.8		
	L	52.6		
	Avg.	50.7		
	T	44.4		
	T	45.5		
	Avg.	45.0	53.6	0.84
8Mo-8V-2Fe-3Al	L	35.8		
	L	30.6		
	Avg.	33.2		
	T	33.4		
	T	33.8		
	Avg.	33.6	34.9	0.96
11.5Mo-6Zr-4.5Sn	L	61.1		
	L	62.3		
	Avg.	61.7		
	T	50.1		
	T	56.1		
	Avg.	53.1	55.1	0.96

The K_{Ic} values of 34.1 to 36.3 ksi$\sqrt{in.}$ obtained in the current study (Table V) agree quite well with those obtained on the 3-inch-diameter press forging. The yield strength of 155 ksi, however, is considerably lower than the 175 to 180 ksi expected for the solution treating and aging temperatures used. The lower yield strength, however, did not result in improved fracture toughness values. The fracture appearance of the specimen shown in Figure 3, flat fracture, with no evidence of shear lip formation is consistent with the low K_{Ic} values obtained.

A review of the processing histories of the press forgings and the two extrusions revealed that in addition to lower reduction ratio of the hollow extrusion the only major difference was that the cylindrical hollow extrusion was water quenched following extrusion. Adair and Roberson[2] have shown that water quenching Beta III immediately following extrusion results in a retention of a significant amount of the dislocation structure produced during extrusion. The retained dislocation structure thus promotes the formation of a fine distribution of the alpha phase during aging. However, they also showed that the K_{Ic} values of water-quenched extrusions were somewhat lower than air-cooled extrusions at the same yeild strength level. Clearly, additional effort is needed in this area to resolve the differences in toughness values obtained on the same heat of Ti-8Mo-8V-2Fe-3Al.

The dynamic fracture toughness K_{Id} values shown in Table VI are slightly lower than the static K_{Ic} values. The K_{Id}/K_{Ic} ratio of 0.96 shows no adverse effect of strain rate for the alloy in the condition studied.

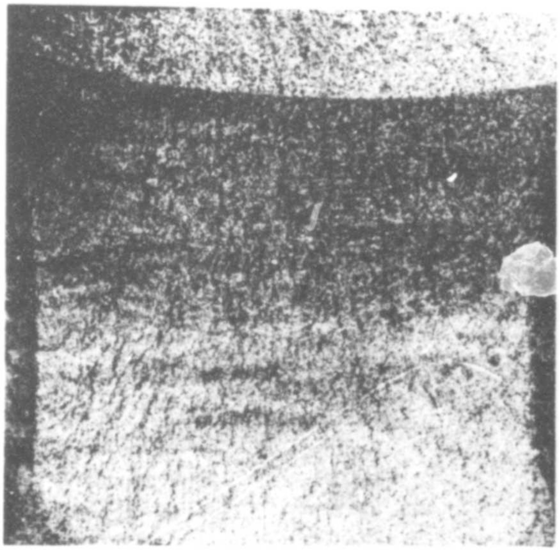
K_{Ic} measurements made on one transverse precracked Charpy specimen in slow bend showed good agreement between valid static K_{Ic} and dynamic K_{Id} values.

Ti-11.5Mo-6Zr-4.5Sn (Beta III)

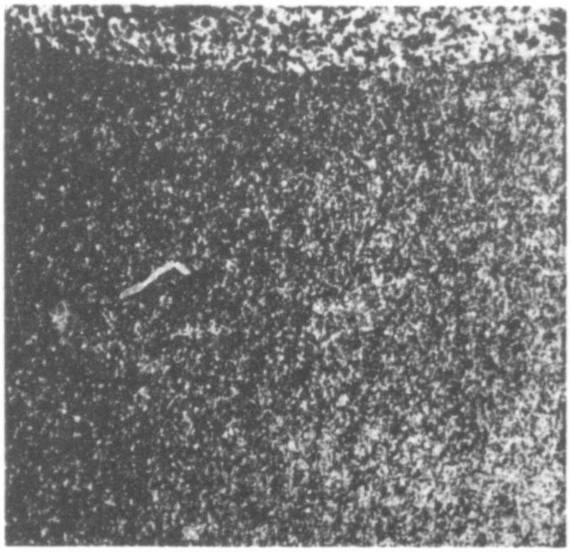
The K_{Ic} values of the Beta III alloy, which ranged from 53.2 to 56.8 ksi$\sqrt{in.}$, were the highest values obtained in the study, Table V. The density of the Beta III alloy, 0.183 lb/in.^{3}, was the highest of the three alloys studied. Normalizing the toughness data for density did not change the rank of the Beta III alloy.

Table VII. K_Q MEASUREMENTS OBTAINED FROM PRECRACKED CHARPY SPECIMENS IN SLOW BEND TESTS

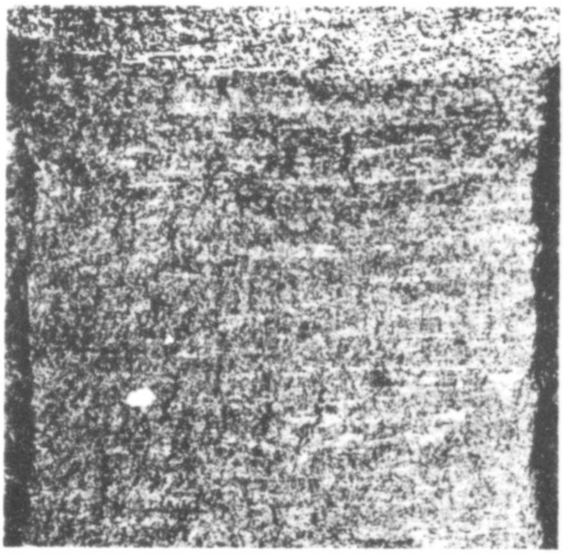
Material	Specimen Orientation	a in.	P_{max} lb	a/W	K_Q	$2.5\left(\frac{K_Q}{\sigma y}\right)^2$
Ti-6Al-6V-2Sn	L	0.131	1870	0.33	52.8	0.300
	T	.121	1750	.31	47.0	.271
Ti-8Mo-8V-2Fe-3Al	L	.129	1140	.33	31.8	.119
	T	.128	1350	.33	37.4	.145
Ti-11.5Mo-6Zr-4.5Sn	L	.139	1880	.35	55.2	.273
	T	.134	1955	.34	56.0	.251



a. Ti-6Al-6V-2Sn



b. Ti-8Mo-8V-2Fe-3Al



c. Ti-11.5Mo-6Zr-4.5Sn

Figure 3. Fracture Surface Appearance of Fatigue Precracked Compact Tension Specimens. Mag. 5X
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The toughness was lower than the 58.9 to 63.4 ksi$\sqrt{in.}$ reported by Broadwell and Coyne on a "Navaho" rib and web forging.[5] Examination of the fracture surface of the compact tension specimen shown in Figure 3 shows rather large shear lips indicative of high toughness.

The K_{Id} values obtained varied from 50.1 to 56.1 ksi$\sqrt{in.}$, Table VI. The K_{Id}/K_{Ic} value of 0.96 showed very little strain rate sensitivity for the material.

The K_{Ic} value of 56.0 ksi$\sqrt{in.}$ obtained on a transverse precracked Charpy specimen, Table VII, is in good agreement with the static values which averaged 55.1 ksi$\sqrt{in.}$ The slow bend data are similar to the 52 ksi$\sqrt{in.}$ obtained by Adair and Roberson[2] on precracked Charpy specimens machined from Beta III extruded at 1500 F at an 11:1 reduction ratio and air cooled from the press.

CONCLUSIONS

The following conclusions are made from this study of three titanium alloy extrusions:

1. The fracture toughness values obtained from the Beta III extrusion were the highest of the three extrusions studied.

2. Solution treating and overaging the 3-inch-diameter extrusion of Ti-6Al-6V-2Sn resulted in moderate yield strength with good fracture toughness.

3. The Ti-6Al-6V-2Sn alloy was adversely affected by strain rate. K_{Id} values were 16 percent lower the K_{Ic} values.

4. Good agreement existed between K_{Ic} values obtained from precracked Charpy V-notch specimens and compact tension specimens. The good agreement suggests that when the 2.5 $(K_Q/\sigma_y)^2$ size requirement is met the three-point (slow) bend precracked Charpy specimen can be used for K_{Ic} screening purposes.

[5] BROADWELL, R. G., and COYNE, J. E. *The Fracture Toughness - Tensile Property Relationships of Deep Hardenable Titanium Alloys.* Spring Meeting AIME, Las Vegas, Nevada, 11-14 May 1970.